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DETECTING SIGNIFICANT SEDIMENT MOTION IN A LABORATORY FLUME USING DIGITAL VIDEO IMAGE ANALYSIS

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ABSTRACT

A video analysis method for monitoring sediment transport and sorting processes in a laboratory flume is presented. Video taken through the glass side-wall of a laboratory flume is captured using a digital CCD (charge-coupled device) camera and significant movements between individual frames are detected using image analysis. This method involves direct subtraction of the brightness numbers of pixels in sequential video frames, followed by thresholding to produce binarized images of significant change, above the inherent level of system noise. Experimental results showing dilation of a gravel framework and rapid infiltration of fines just prior to entrainment are discussed. Copyright © 2000 John Wiley & Sons, Ltd.

KEY WORDS: digital video; image analysis; sediment transport

INTRODUCTION

The use of photography in sediment transport research is not new and many authors report the use of either cine or video photography for the detection of particle movement in water (e.g. Hammond *et al.*, 1984; Drake *et al.*, 1988). Most research employing video image analysis has, however, generally concentrated on monitoring the timing of bedload entrainment or particle transport distances and relating these data to experimental hydraulic and sedimentological conditions. Rather less attention has been directed towards monitoring particle sorting processes and the whole behavior of sediment aggregates undergoing entrainment. Recent experimental research by Allan and Frostick (1999) and Middleton *et al.* (in press) has suggested evidence of significant dilation of framework gravels just prior to entrainment. They inferred that this dilantancy may also be responsible for the rapid infiltration of near-surface fines deep into the bed, a process which may, at least partially, explain reverse grading in fluvial gravel deposits. Such sorting of matrix and framework sediments has potentially important implications for streambed permeability, stream ecology and the deposition of economically significant placers such as diamonds and gold.

This paper reports a method of monitoring small movements of clasts just prior to entrainment and the ingress of fine matrix material into framework gravels using digital image analysis. The method presented involves the analysis of digital video imagery taken through the glass side-wall of a laboratory flume and builds upon the earlier research of Allan and Frostick (1999). The use of modern CCD (charge-coupled

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Table I. Camera response and background noise: DN for each band across grey-scale range with standard deviation in brackets

	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19
Red	255 (0)	255 (0)	244 (2)	221 (2)	199 (2)	182 (2)	164 (2)	149 (3)	130 (3)	113 (3)	97 (3)	81 (3)	72 (3)	62 (3)	53 (2)	49 (2)	43 (3)	39 (3)	36 (2)
Green	255 (0)	255 (1)	229 (2)	210 (2)	189 (2)	171 (2)	153 (2)	138 (3)	119 (2)	103 (3)	89 (3)	75 (2)	66 (3)	57 (2)	50 (2)	46 (2)	41 (2)	38 (2)	35 (2)
Blue	255 (0)	254 (2)	228 (3)	209 (2)	189 (2)	170 (2)	151 (3)	135 (4)	118 (3)	103 (4)	88 (3)	75 (3)	68 (3)	57 (3)	51 (3)	46 (3)	42 (3)	38 (3)	36 (5)

device) camera technology yields easily calibrated images in a ready-to-use digital form, avoiding the need for time-consuming digitization and analysis of analogue images.

In the original research, Allan and Frostick (1999) used a simple method to monitor sorting processes in a sand–gravel mixture within a laboratory flume. Their technique involved the direct subtraction of the image brightness values (digital numbers 0–255) of consecutive video frames sampled at 25 Hz to produce an image of 'relative change' scaled between 0 and 255. While potentially diagnostic, this technique fails to account for background noise of the imaging system, which may result in artefacts in the resultant 'change' image. This paper presents refinements to this method in which, after an evaluation of the inherent noise in the imaging system, binarized images of significant change between frames are produced. An example of the method applied to monitor movements in a sand–gravel mixture undergoing entrainment is presented.

THE IMAGING SYSTEM

A commercial Sony DCR-VX700E digital video camera that images with a single, precision 1/3" CCD was used to monitor particle movement. The output image of the camera has a resolution of 720×576 pixels and is generated at a rate of 25 Hz (0·04 s). Each pixel in the image is a 24-bit value representing the intensity of reflected blue, green and red light as a digital number (DN) on a scale of 0–255. Individual frames actually comprise out-of-phase odd and even scan-lines sampled at 50 Hz which are interlaced using interline transfer methods. The spectral response of the CCD is not uniform across the three colour bands. Maximum precision is afforded in the red and green bands while the blue band image is degraded to minimize the bandwidth for signal transmission. The camera records directly to digital tape and time and date-stamped images are captured via a Firewire (IEEE 1394) enabling lossless transmission. Captured images are converted directly into three bitmaps, one for each colour band.

SYSTEM NOISE

Any image analysis method is sensitive to the effects of under-sampling, light scattering, aberrations in the camera lens and, for CCD cameras, electronic noise and the effects of integration and variation in the sensitivity of the individual CCD elements. While sampling resolution and to some extent the effects of scattering are a function of the experimental conditions, the integrated effects of lens and CCD defects are inherent to the imaging system and represent the background noise of the instrument. This noise level was evaluated by an analysis of images taken of a standard Kodak photographer's grey-scale calibration step wedge. The grey-scale used was composed of 20 density steps with reflection densities of 0·05 to 1·95 in 0·1 intervals (2·5 = perfect absorption). Twenty experiments were conducted in which the camera was restarted to account for small variations in illumination and vibration and single frames of the grey-scale wedge captured. Within each interval of the grey-scale a rectangular area of 20×60 pixels was examined revealing standard deviations in the range 2–3 DN for the red and green channels and 3–4 DN for the blue, with no apparent

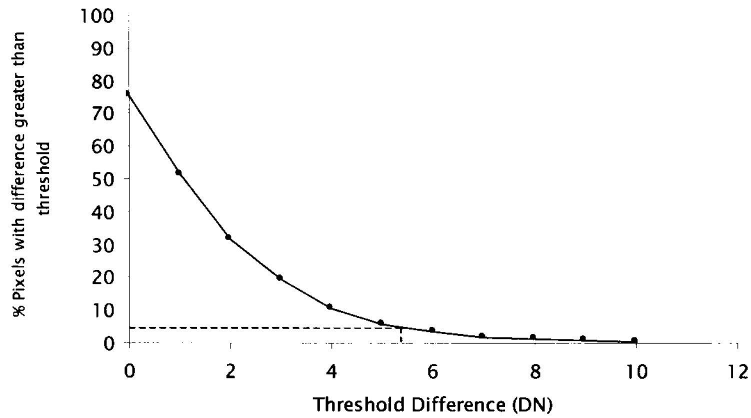

Figure 1. Percentage image error at different threshold values of change (DN)

relationship between the noise level and DN (Table I). As expected, the blue band exhibits the highest noise and later analyses were conducted using the green band.

IMAGE SCALE CALIBRATION

The camera image must be calibrated to allow conversion of pixels into actual distances. This was achieved by imaging a precision graduated ruler and deriving the image scale:

$$S = \frac{P_n}{x} \tag{1}$$

where S is the image scale, x is a known distance (m) and P_n is the number of pixels covering the known distance. The actual image scale is a function of the camera focal length and imaging distance. Checks on the vertical and horizontal scaling of the images revealed the image pixels to be slightly off-square with the vertical dimension 2·8 per cent longer than the horizontal. This aspect ratio was built into all derivative calculations.

IMAGE ANALYSIS

The imaging system described above generates 25 frames per second, each showing the distribution of reflected energy in three colour bands. Movement in the image between frames (0·04 s) can be detected by directly comparing the brightness values of like pixels in successive images. As demonstrated above, however, some differences between images of exactly equal scenes may be expected due to aberrations in the lens and CCD and also due to small variations in illumination and camera vibration. There is therefore a need to identify the lower limit of detection and differentiate between significant and spurious differences between frames. Analysis of the grey-scale step wedge discussed above suggested pixel standard deviations of 2–3 DN for the green and red bands, with no significant variation across the dynamic range. Any comparison of two images clearly incorporates errors from both, so that the standard deviation of differences between pixels (Eq. 2) should lie in the range *c*. 3–5:

$$s_d = \sqrt{(s_1)^2 + (s_2)^2} \tag{2}$$

where S_1 and S_2 are the standard deviation of DN of pixels in the raw images, and s_d is the standard deviation

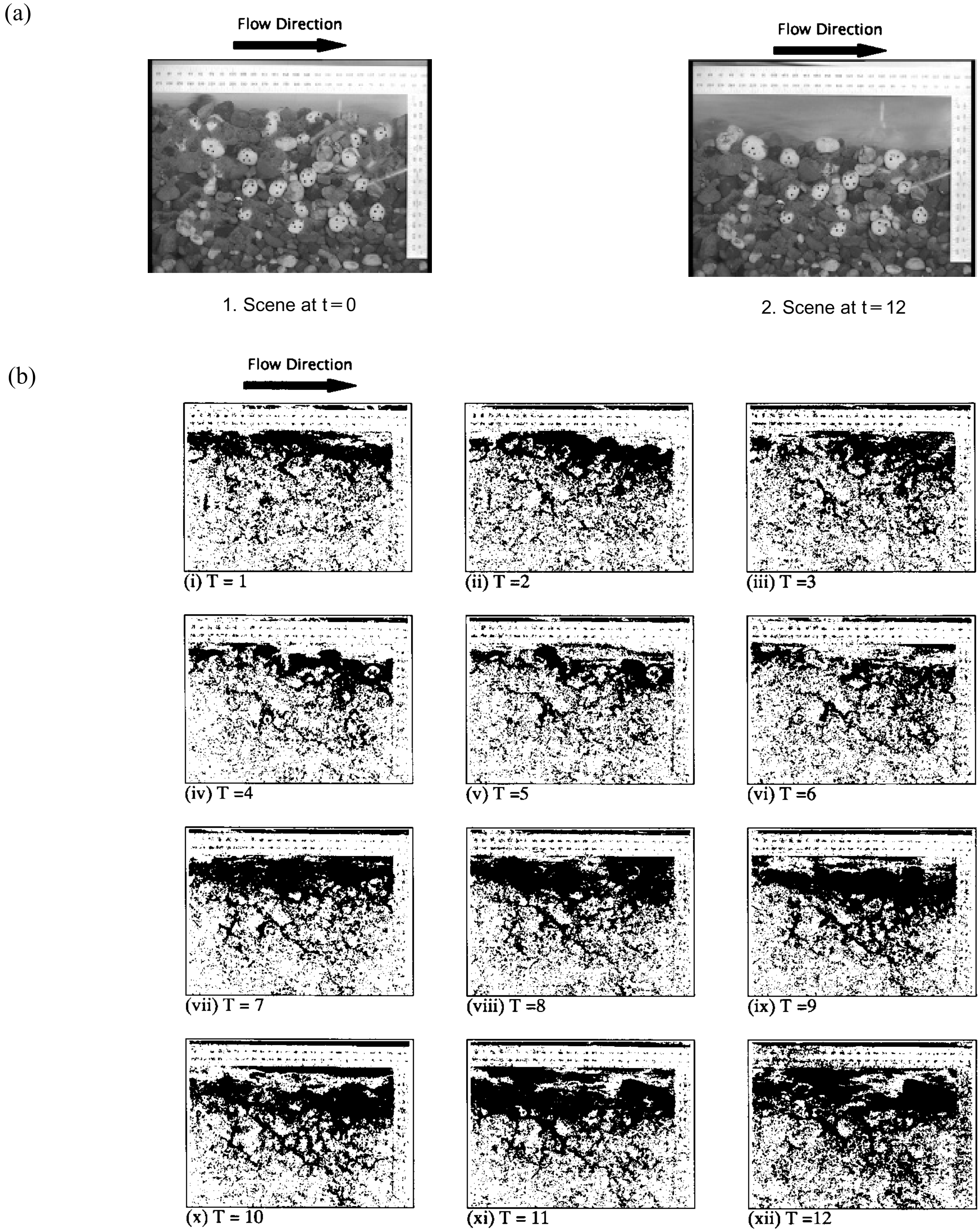

Figure 2. (a) Framework dilation and infiltration of matrix sands during erosion of the surface layer. Image 1 shows initial conditions; image 2 shows the bed structure 12 s later (precision steel rulers used for scale derivation). (b) Images (i)–(xii) show changes between frames at a 1 s interval which indicate framework dilation and infiltration of matrix sands

of the differences. This implies that changes of greater than 6–10 DN (2 s) could be considered statistically significant at the 95 per cent level. Given the integer scale of the brightness numbers, this assessment is clearly somewhat crude. Direct comparison of two 'equal' images of a photographer's test card, in which the camera was restarted between the captured images, demonstrated a somewhat lower actual limit of detection. Figure 1 shows the relationship between percentage image error (per cent changed pixels) computed for different thresholds of change (DN). This analysis suggests that differences in DN of 6 or more can be treated as significant at the 95 per cent confidence level.

Direct analysis of successive frames also requires consideration of the effects of image interlacing. As described above, images generated by the Sony camera are composed of interlacing odd and even scan-lines sampled out of phase at a sampling rate of 50 Hz. Simple differencing of consecutive images will, therefore, incorporate a temporal off-set between scan-lines of 0·02 s. In order to distinguish artefacts generated by this effect, each image is de-interlaced prior to analysis, by splitting odd and even scan-lines and creating two images in which the missing odd or even line, respectively, is replaced with a replica of its adjacent scan-line. It should be noted that while this compromises the vertical resolution of the analysis, the image remains internally consistent.

The effects of system noise and image interlacing were incorporated into the design of a new image subtraction algorithm developed to produce binarized images of change between frames (black = significant change; white = no change) at user-defined threshold levels of DN. The algorithm allows for batch processing of consecutive video frames and produces a series of 'change' images which can be animated.

EXPERIMENTAL RESULTS

In order to re-evaluate the dilation process observed by Allan and Frostick (1999), this image analysis method was applied to monitor the motion of gravel framework clasts in a glass-sided laboratory flume just prior to entrainment. A recirculating flume, 9 m long, 0·3 m wide and 0·5 m deep with a working section of approximately 3 m, was used in the experiments. The video camera was positioned orthogonal to the flow at a distance of 2·5 m from the sidewall and 6·5 m downstream from the intake. The pixel resolution was calibrated to 0·31 mm. The flume slope was set to 0·025 per cent and a gravel framework of chert and quartz gravels with a D_{50} of 5·8 mm was constructed to a depth of *c.* 0·2 m.

The framework was left to consolidate for 1 h under sub-critical flows then 12 kg of sand (D_{50} = 0·6 mm) was introduced upstream and left to migrate downstream for a period of 6 h. To evaluate matrix sediment sorting processes under high flows a flood was simulated in the flume channel, in which flows were rapidly elevated above the critical entrainment threshold for the gravel D_{85}. The motion of the sediment aggregate was filmed during this event and 15 s of video (375 frames) were captured for the period during which the gravel framework in the field of view was actively eroded. The captured images were converted to single (green) band bitmaps and the algorithm used to automatically identify significant changes ($>$ 6 DN) through the series of images. Figure 2a and 2b shows the erosion and sorting of the sediment mixture over a 12 s period as the bed is entrained. Figure 2b shows areas of significant difference between frames separated by a 1 s interval.

Between 1 and 6 s into the simulation, the infiltration of sands along interconnected interstitial pore spaces is evident as black lines trending from left to right in the direction of flow. Above this, entrainment of the surface clasts and overpassing of gravels can also be visualized. Between 7 and 12 s into the simulation, the framework begins to dilate to a depth of three to four clasts, evidenced by the black halos surrounding the framework clasts. Dilation is localized in areas above distinct downstream-trending pores which appear to be acting as shear planes. As the framework dilates, initially negative pore pressures induced by the expansion could be hypothesized to induce rapid flow into the framework, reinforcing the dilative tendency causing fine sediment to be actively migrated down-profile. Some concern may exist in that the patterns observed here occur close to the rigid glass wall of the flume and may therefore not be representative. To evaluate the effect of the wall, a cross-section of the bed was frozen in liquid nitrogen and extracted. Cross-stream sampling of the bed material showed no significant difference in the distribution of fines, and the pattern matrix of fines at

depth was uniform across the flume. Further experimentation using an array of micro-pressure transducers is also being developed to monitor actively the pressure distribution across the flume channel.

CONCLUSIONS

A simple image analysis technique based on differencing the brightness number of successive digital video images has been presented, in order to visualize and quantify sediment transport processes. Binarized images showing areas of change between individual frames are produced which are significant above the range of system noise. An application of the method to monitor transport and sorting processes in a sand–gravel mixture has demonstrated the diagnostic power of this visualization tool. While designed specifically with this application in mind, the technique could be used to monitor a variety of dynamic processes imaged with digital video photography.

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